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Research Article

EXPERIMENTAL AND STATISTICAL ANALYSIS ON MACHINABILITY OF NIMONIC80A SUPERALLOY WITH PVD COATED CARBIDE

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ABSTRACT

Nimonic80A is a new superalloy which is used in aerospace technology due to its resistance against high temperature and oxidation. This study addresses an investigation of machinability outputs on Nimonic80A superalloy, including cutting forces and surface roughness. Turning experiments on different cutting conditions with PVD coated carbide were carried out on CNC lathe to determine the cutting forces and surface roughness. Three different cutting parameters, namely cutting velocity, cutting depth and feed rate are used with three different levels. The effect levels of the cutting parameters are determined with analysis of variance (ANOVA) with 95% confidence level. Then, a regression model is applied to predict the results of cutting forces and surface roughness in the certain range of cutting conditions. The results show that the cutting depth has the highest significance on main cutting force (F_c) and feed force (F_f) while the feed rate has the highest significance on radial force (F_r) and surface roughness (R_a). The cutting velocity has much less effect onto cutting force when it improves surface roughness. Finally, the deviation between experimental and second order regression model results for F_c, F_r, F_f and R_a are calculated as 4.53%, 3.21%, 7% and 9.12%, respectively.
Keywords: Nimonic80A, turning, cutting force, surface roughness, regression model.

1. INTRODUCTION

In machining processes, excesses on the workpiece may be discarded using a suitable machine tool and insert so that the workpiece can reach the desired size and surface quality. In this process; the relationship between the independent variables such as cutting parameters (cutting depth, feed rate, cutting velocity), cutting fluid, workpiece material, tool material, tool geometry, machine tool and the dependent variables such as cutting forces, surface quality, cutting tool life, cutting temperature should be evaluated well [1]. The cutting forces are one of the important issues in machining because they directly affect the performance of the cutting tool. In addition, the cutting forces must be efficiently analyzed by manufacturers of machine tools. Because if the machine tool power is known what it is supposed to be, the pieces of the tool can be designed as rigid and vibration-free, which can withstand the resulting stresses. The selection of the machining parameters for both machining method and materials type has been considered

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by many researchers for y ears and is still investigated to determine the optimum cutting conditions [2].

Nickel-based superalloys are generally known as the materials that are resistant to environmental conditions and exhibit the required strength under operating conditions of 260°C - 1200°C [3]. These materials, especially Nimonic80A are commonly used in turbine engines [4], power units, furnaces and also in the manufacturing of fasteners parts [5]. Nickel-based superalloys, on the other hand, are among the most difficult to machine due to their high thermal-mechanical properties [6]. Especially, since the researches on machining are expensive and time consuming [7], mathematical modeling of the cutting process is applied as an alternative solution method [8-10]. The most preferred model is the regression model among the mathematical modeling methods used in the modeling of the cutting process [11]. During chip formation process; tremendous improvements were provided by means of mathematical models that help to predict the cutting forces, surface quality, temperature, and stress values in machining processes [11-13]. Thus, the cutting conditions can be optimized in the machining operations and it is possible to make a significant contribution to decrease the cost by reducing the tooling cost [7]. In this sense, the mathematical models have become an indispensable tool in the analysis of engineering designs and manufacturing processes. Kumar et al. investigated on machinability of AISI D2 steel and its mathematical modeling with regard to cutting temperature, surface roughness and flank wear. The authors confirmed their model with high accuracy and proposed it for future researches [14]. Boujelbene focused on turning processes of Ti6Al4V alloy to determine the tangential cutting force and developed a mathematical model to predict the force without the need for experiments [15]. Saini et al. performed turning experiments on AISI H11 steel via ceramic tool with different cutting parameters. Then, a regression model was developed in order to forecast the machining output such as residual stresses and also to specify the effects of parameters on this output [16]. Koyee et al. investigated the modeling on turning of EN 1.4462 and 1.4410 steels. The model was found in high accuracy with experimental study [17]. Finally, many recent studies have been investigated on mathematical modeling of machining, especially turning of engineering materials as well as experimental studies [18-20].

The majority of past studies emphasized the importance on mathematical modeling of machining processes with many different engineering materials. However, there is not enough machining or modeling study on a new superalloy that is recently used in aerospace area. Therefore, the present study aims the experimental and mathematical modeling on machinability of Nimonic 80A superalloy with PVD coated carbide.

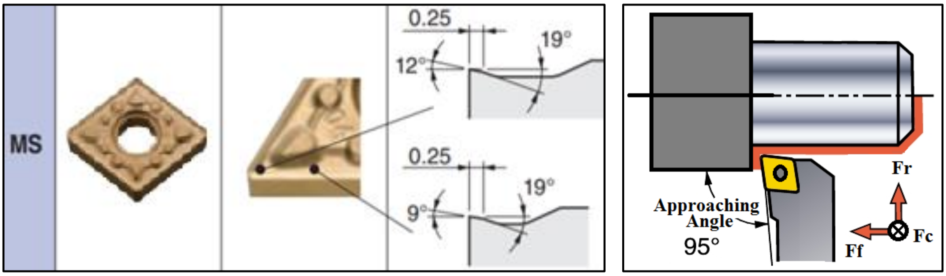
2. MATERIAL AND METHOD

2.1. Experimental Study

In experimental work, Nimonic 80A superalloy was used as workpiece material, as a result of the literature survey, on which no machining process was performed before. Chemical composition of workpiece material is given in Table 1. The workpiece dimensions are Ø40x250 mm and the hardness of the material used in the tests is 290 HV. In the experiments, CNGN 120408-MS coated carbide cutting tools, by Kyocera, were used as inserts having tool nose radius (r_ε) of 0.8 mm. These inserts with MS (γ; chip breaker angle 19°) chip breaker geometry (Fig. 1a) are rigidly connected to the tool holder in the form of PCLNR 2525M12 with an approaching angle (χ_r) of 95° on the CNC lathe.

Table 1. Chemical composition of Nimonic 80A.

C	Si	Mn	P	S	Al	Co	Fe	Ti	Cr	Ni
0.052	0.06	0.02	0.005	0.001	1.35	0.05	0.8	2.43	19.2	Balance



a) b)

Figure 1. Ch ip breaker geometry on the inserts

The levels of cutting parameters were determined based on the cutting tool manufacturer's recommendation and literature reviews. Three different levels of cutting depth (*a*), cutting velocity (*V*) and feed rate (*f*) were selected and given in Table 2. The tests were carried out on a TC 35 Johnford CNC lathe with Fanuc control unit according to the parameters.

Table 2. The parameters and levels

Turning Parameters	Level 1	Level 2	Level 3
a (mm)	0.5	1	1.5
V (m/min)	45	60	75
f (mm/rev)	0.1	0.2	0.3

Firstly, measuring of cutting forces were provided by a 9257B type dynamometer. The cutting force data perceived by the dynamometer was taken to computer using Kistler Type 5019B130 Multichannel Charge Amplifier using Type 2855A3A / D Board CIO-DAS 1602/12 data acquisition card and Kistler Type 2825A1-2 Dynoware software. The cutting forces components (Fig.1b) were obtained by dynamometer and equipment mentioned above. As a second part of the study, surface quality was investigated by measuring surface roughness values (R_a) via Mahr Perthometer M1 device. The Ra values was evaluated by taking average of three values measured from each 120° of cylindrical part. Finally, regression models were performed for the cutting force components and the surface roughness. The stages of the experimental setup and the regression analysis are schematically shown in Fig. 2.

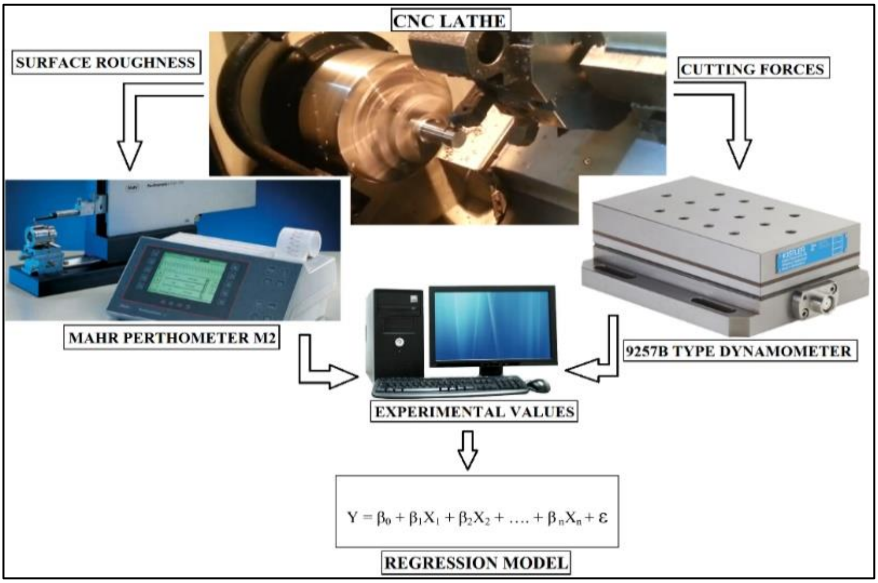


Figure 2. The stages of the study

2.2. Regression Analysis

Regression analysis is used to determine the relationship between two or more variables that have causal relation between them and to make predictions or estimations about that topic using this relation. In this analysis technique, a mathematical model is used to describe the relationship between two (simple regression) or more variables (multiple regression), and this model is called the regression model. In this study, the multiple regression is performed due to having three independent variables (cutting velocity, feed rate and cutting depth) and four dependent variables (cutting force components and surface roughness) [2].

The cutting parameters directly affecting the cutting forces and surface roughness have a great importance in terms of the validity and reliability of the models to be developed for force components (F_c, F_f and F_r) and surface roughness (R_a). For this reason, cutting parameters, namely cutting velocity, feed rate and cutting depth are taken into consideration in the developed model of cutting forces and surface roughness separately. Therefore, it is aimed to develop the models of cutting forces and roughness which is easy to apply to real cutting conditions that is economical, understandable, high reliable by using basic cutting parameters.

3. RESULTS AND DISCUSSION

3.1. Main Cutting Force (F_c)

The main cutting force (F_c) values which are important at the primary level in terms of energy consumption in turning are firstly taken into account in the analysis of the cutting forces. The F_c values have about 50% increase with increasing feed rate from 0.1 to 0.2 mm/rev while this increase rate is about 30% by the feed rate from 0.2 to 0.3 mm/rev as shown in Fig. 3. This variation in the main cutting force is similar for each cutting depth. The Fc values have about %65 increase with increasing cutting depth from 0.5 to 1 mm while %35 increase by cutting depth from 1 to 1.5 mm (Fig. 3). This increasing trend in the Fc is also obtained for each feed rate. On the other hand, there is decreasing trend by increasing cutting velocity as expected but the decreasing ratio is inconsiderable as also seen from the result of variance analysis. The minimum F_c value is measured as 242 N in cutting depth of 0.5 mm, feed rate of 0.1 mm/rev and cutting velocity of 45 m/min.

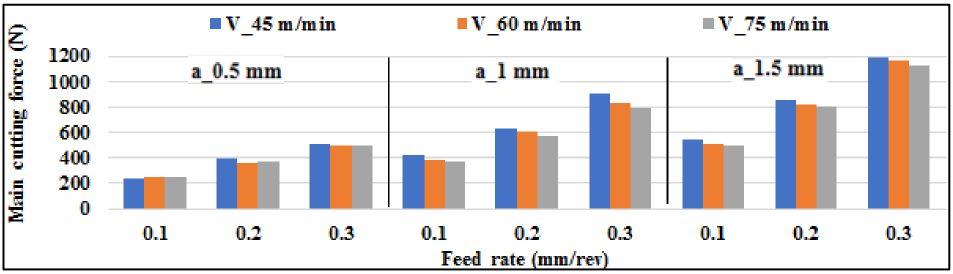


Figure 3. The distribution of F_c values

The experimental results are also evaluated with analysis of variance (ANOVA) with 95% confidence level to determine the effects of parameters on machining outputs, namely F_c, F_r, F_f and R_a. According to ANOVA results, *P* values must be less than 0.05 to understand that the parameter is effective on the machining outputs. Table 3 shows that the cutting depth is the most important factor on F_c with 47.8% PCR (Percentage contribution ratio). It can be said that the feed rate is the secondary important parameter on cutting forces (45.88% PCR), nevertheless the cutting velocity has inconsiderable effects on the F_c.

Table 3. ANOVA results for F_c.

Source	Degree of Freedom	Sum of Square	Mean Square	F	P	PCR
V	2	10566	5283	0.92	0.416	0.53
f	2	915767	457883	79.34	0.000	45.88
a	2	954171	477086	82.67	0.000	47.81
Error	20	115420	5771			5.78
Total	26	1995925				100

3.2. Radial Force (F_r)

The radial force (F_r) values which are generally the lowest one of the cutting force components in conventional cylindrical turning operation. The F_r values is lower than the F_f values for the cutting depth of 1 and 1.5 mm as expected, but higher for the cutting depth of 0.5 mm. Since the tool nose radius (0.8 mm) is higher than cutting depth, the radial force is higher due to chip formation occurs depending on ploughing effect. It is valid only for the cutting depth of 0.5 mm that the F_r values have about 25% increase with increasing feed rate both from 0.1 to 0.2 mm/rev and from 0.2 to 0.3 mm/rev. This increase ratio is 50% by increasing the feed rate in the range 0.1-0.3 mm/rev for the cutting depth of 1 and 1.5 mm as shown in Fig. 4.

The F_r values have a little change by increasing the cutting depth (Fig. 4) as indicated Ref [21-22]. The tool-chip contact area and so the force distribution is smaller than that of other forces depending on approaching angle of cutting tool. Therefore, the *Fr* component has little increment by increasing cutting depth due to less change of the tool-chip contact area on Fr direction. Moreover, the F_r values are generally decrease by increasing cutting velocity as seen in Fig.4

[21]. The minimum F_r value is obtained as 142.3 N in cutting depth of 0.5 mm, feed rate of 0.1 mm/rev and cutting velocity of 75 m/min.

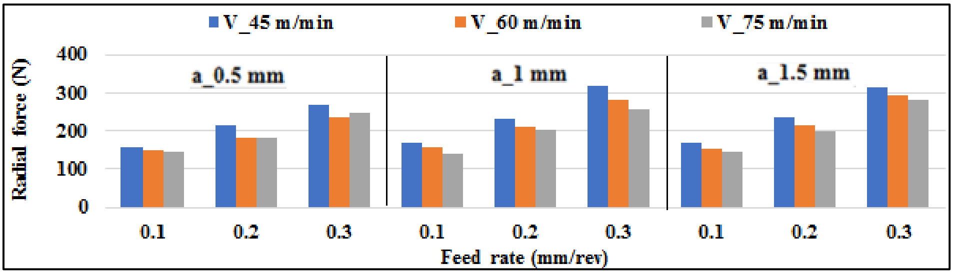


Figure 4. The distribution of F_r values

According to ANOVA results, Table 4 shows that all cutting parameters is important for F_r, however the feed rate is the most important factor on the F_r with 87.63% PCR. Moreover, the cutting velocity is the secondary important parameter with 5.14% PCR while the cutting depth is the less important parameter with 4.47% PCR.

Table 4. ANOVA results for F_r.

Source	Degree of Freedom	Sum of Square	Mean Square	F	P	PCR
V	2	3998	1999	18.66	0.000	5.14
f	2	68183	34092	318.15	0.000	87.63
a	2	3481	1741	16.24	0.000	4.47
Error	20	2143	107			2.76
Total	26	77806				100

3.3. Feed Force (F_f)

Feed force which is parallel to the feed direction, can generally be up to about 55% of the force F_c. The relationship between the feed force (F_f) and the radial force (F_r) was explained in detail the part of the radial force (F_r). It is valid for all the cutting depth that the F_f values have about 18% increase with increasing feed rate both from 0.1 to 0.2 mm/rev and 24% increase by the feed rate from 0.2 to 0.3 mm/rev as seen from Fig. 5. The F_f values have 90% increase by increasing the cutting depth from 0.5 to 1 mm while 35% increase from 1 to 1.5 mm. On the contrary, the cutting velocity has reducing effect on the F_f values by 13% and %10 when it increases from 45 to 60 m/min and from 60 to 75 m/min, respectively (Fig. 5). The minimum F_f value is obtained as 123.7 N in cutting depth of 0.5 mm, feed rate of 0.1 mm/rev and cutting velocity of 75 m/min.

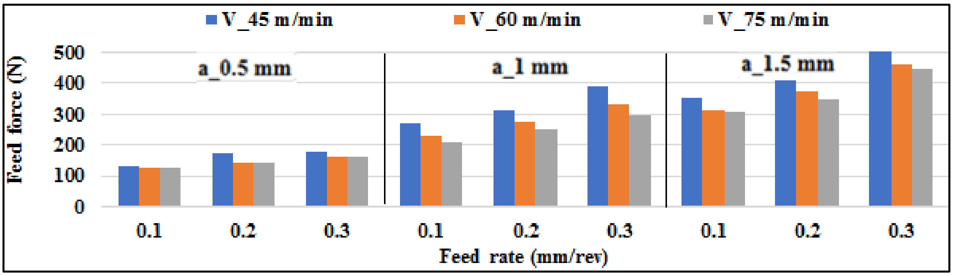


Figure 5. The distribution of *Ff* values

The most significant parameter on F_f is the cutting depth with 80.17% PCR (Table 5). It can be seen that the feed rate is the secondary important parameter with 12.52% PCR while the cutting velocity has 3.49% PCR.

Table 5. ANOVA results for *Ff*.

Source	Degree of Freedom	Sum of Square	Mean Square	F	P	PCR
V	2	11719	5859	9.20	0.001	3.51
f	2	41954	20977	32.92	0.000	12.52
a	2	268570	134285	210.75	0.000	80.16
Error	20	12743	637			3.81
Total	26	334986				100

As a whole, the increase in cutting forces with increasing feed rate (*f*) and cutting depth (*a*) is expected situation in machining processes [23,24]. As a reason of this result, it is possible to show the increase in the tool-to-chip contact area and so the energy consumption increases in chip formation by the increase in *f* and *a* value. The cutting forces display regular and expected tendency, especially for the cutting depth of 1 and 1.5 mm. However, irregular tendency in cutting depth of 0.5 mm (smaller than tool nose radius of 0.8 mm) can be referred to ploughing effect. The ploughing process are shown by the effect of minimum cutting depth, especially in F_r and F_f cutting force components. The increase in ploughing force is resulted from uncut chip thickness or cutting depth which is less than a critical value ($a \geq r_\varepsilon$) [25-28], that is micromachining process. Thus, unexpected tendencies for F_r and F_f are observed only in the minimum cutting depth.

3.4. Surface Roughness (R_a)

The improved surface quality increases fatigue strength, wear resistance and decreases the corrosion behavior of the finished parts. The surface roughness depends on various factors like material hardness, tool material and geometry, coating material, heat transfer and cutting parameters. Hence the optimized surface roughness is important, especially for good surface quality [29-30] owing to requirement of high strength in assembly operations in defense and aerospace industry where nickel-based superalloys are frequently used in recent times.

The surface roughness values increase with increasing feed rate as expected for all cutting velocity and cutting depth. The R_a values have about 160% increase with increasing feed rate from 0.1 to 0.2 mm/rev while this increase rate is about 135% by the feed rate from 0.2 to 0.3 mm/rev for all cutting velocity and cutting depth values as shown in Fig. 6.

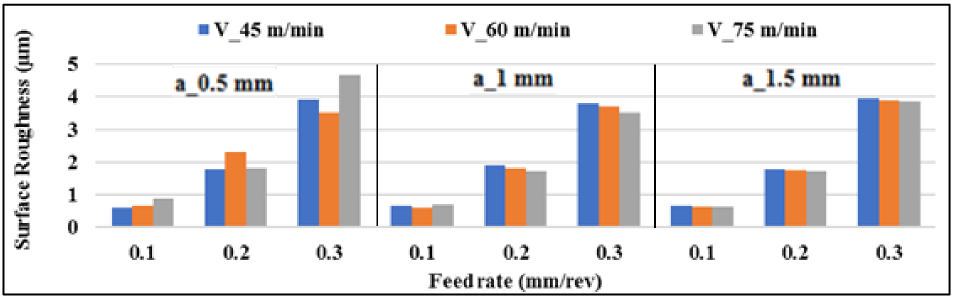


Figure 6. The distribution of R_a values

The cutting velocity has additive effect on R_a values for the cutting depth of 0.5 mm due to ploughing effect mentioned above. The surface roughness increases considerably when the cutting velocity is 75 m/min in the minimum cutting depth. On the other hand, in higher cutting depths surface quality improves with increasing cutting velocity. This shows that the nickel-based superalloy should be machined in medium cutting velocity (60 m/min) and low feed rate in order to obtain high surface quality. The Fig. 6 also demonstrates that the cutting depth has very low effect on the surface roughness once tool nose radius is bigger than cutting depth. The minimum R_a value is obtained as 0.6 µm in cutting depth of 1 mm, feed rate of 0.1 mm/rev and cutting velocity of 60 m/min. Table 6 shows that the feed rate is the most and only significant parameter on Ra with 97.39% PCR.

Table 6. ANOVA results for R_a.

Source	Degree of Freedom	Sum of Square	Mean Square	F	P	PCR
V	2	0.0249	0.0125	0.23	0.795	0.06
f	2	47.4369	23.7185	440.92	0.000	97.39
a	2	0.1766	0.0883	1.64	0.219	0.36
Error	20	1.0759	0.0538			2.19
Total	26	48.7143				100

3.5. Regression Model

The multiple regression model is developed to predict the cutting forces and surface roughness without needs for the experiments in these cutting conditions. The models are the second-degree regression models for both cutting forces (F_c, F_r and F_f) and surface roughness shown in Eqn. 2-5, respectively.

$$F_c = (7.33 - 0.0301 * V + 45.64 * f + 9.377 * a)^2 \quad (2)$$

$$F_r = (11.334 - 0.03164 * V + 21.036 * f + 0.874 * a)^2 \quad (3)$$

$$F_f = (8.696 - 0.0475 * V + 13.97 * f + 7.582 * a)^2 \quad (4)$$

$$R_a = (0.2332 + 0.00066 * V + 5.767 * F - 0.0484 * a)^2 \quad (5)$$

The coefficients of determination (R^2) show the relation between independent (V, f, a) and dependent variables (F_c, F_r, F_f, R_a) and are found as 0.9778, 0.9702, 0.9638, 0.9707 for main cutting force, radial force, feed force and surface roughness, respectively (Fig. 7-10). Furthermore, the deviation between experimental and modeling results for F_c, F_r, F_f and R_a are calculated as 4.53%, 3.21%, 7% and 9.12%, respectively. The coefficients of determination and deviation values prove that these models are accurate and can be reliably used in related industries working on the material.

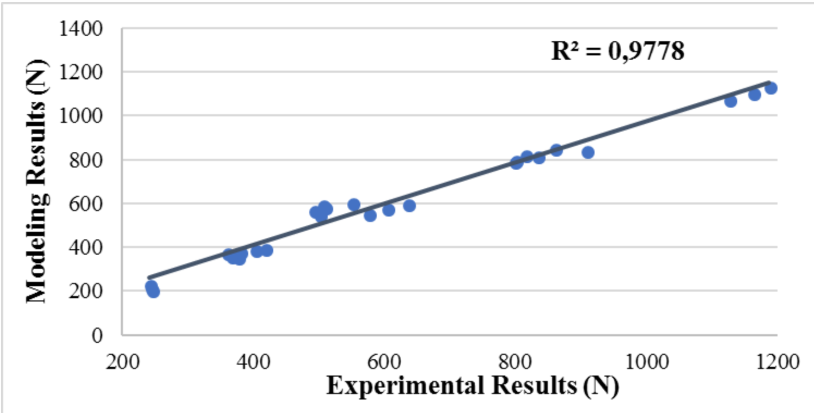


Figure 7. The comparison of experimental and modeling results for F_c

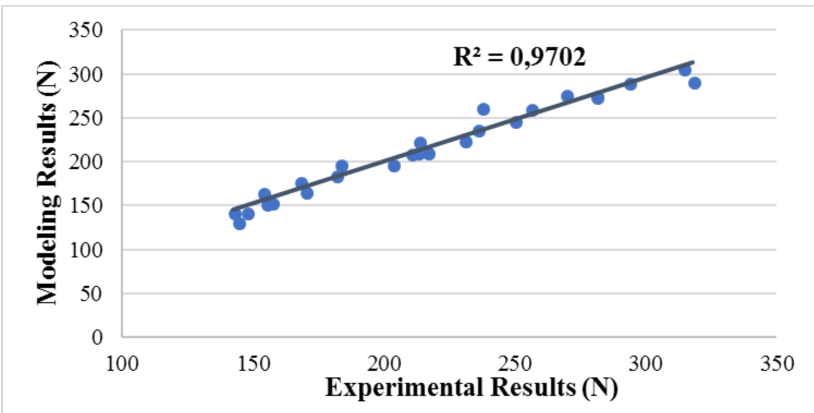


Figure 8. The comparison of experimental and modeling results for F_r

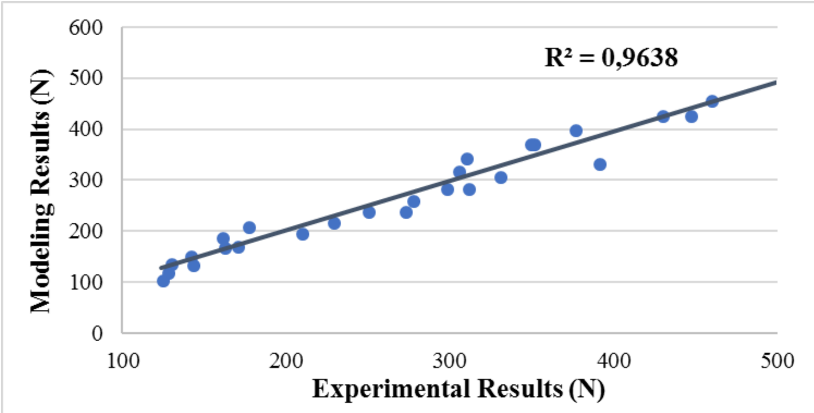


Figure 9. The comparison of experimental and modeling results for F_f

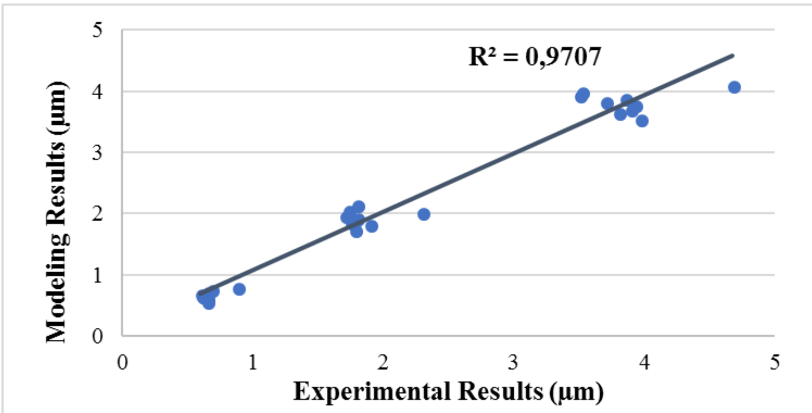


Figure 10. The comparison of experimental and modeling results for R_a

4. CONCLUSIONS

This paper presents the experimental study and mathematical modeling on machinability of new technological Nimonic 80A superalloy with PVD coated carbide. The aim of the study is to shed light on the future researches that are investigated on this superalloy. The summarized conclusions are listed below.

- The increase in cutting forces with increasing feed rate (*f*) and cutting depth (*a*) is expected situation in machining processes. As a reason of this result, it is possible to show the increase in the tool-to-chip contact area and so the energy consumption in chip formation by the increase in *f* and *a* values. The cutting forces shows irregular tendency, especially for F_r and F_f components in cutting depth of 0.5 mm can be referred to ploughing effect since the tool nose radius for the inserts is 0.8 mm while cutting depth is 0.5 mm.
- The F_r values have a little change by increasing the cutting depth. The tool-chip contact area and so the force distribution is smaller than that of other forces depending on approaching angle of cutting tool. Therefore, the F_r component has little increment by increasing cutting depth due to less change of the tool-chip contact area on F_r direction.

- This nickel-based superalloy should be machined in medium cutting velocity and feed rate in order to obtain high surface quality. Moreover, the cutting depth has inconsiderable effect on the surface roughness.
- The modeling results of F_c, F_r, F_f, R_a are deviated from that of experimental results with 4.53%, 3.21%, 7% and 9.12%, respectively. These deviation values verify that these models are precise and can be suitably used in upcoming studies for related industries.

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